FINAL REPORT

Title: Can the arrangement of pine barrens mediate the spread of wildfires under various climate change scenarios?

JFSP PROJECT ID: 14-3-01-32

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Table of Contents

List of Table and Figures

Acknowledgements

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Abstract

Jack pine barrens were once common in fire-adapted, dry sand prairie ecosystems in northern Lower Michigan, where open barrens dominated by grasses, forbs, and low shrubs persisted within dense jack pine forests. This structure was historically maintained by frequent, stand-replacing wildfires prior to 20th century fire suppression. Suppression of wildfires has concomitantly reduced the extent of young jack pine forests in the region, which comprise the majority of breeding grounds for federally endangered Kirtland's warblers. Modern forest management prioritizes provision of Kirtland's warbler habitat through extensive jack pine plantations, although barrens are rarely included in management plans, and the landscape has become increasingly altered. Barrens act as refugia for rarer grassland species and potentially as fuel breaks, facilitating wildfire management in a populated, fire-prone region while maintaining landscape heterogeneity. However, changing climate conditions may preclude natural barrens creation due to changes in temperature and precipitation that could encourage woody plant encroachment. We used the spatially-explicit, forest landscape simulation model LANDIS-II to model the capacity of barrens to act as natural fuel breaks on the landscape. We also simulated effects of altered climate using projected climate scenarios to quantify potential changes in barrens distributions. Landscapes simulated using 30-year normals (PRISM) for temperature and precipitation were compared with simulations using the Hadley Climate Centre A1FI scenario. We found that areas with low primary productivity, interpreted as barrens, can act as fuel breaks by preventing future fires in those areas for decades, and can therefore aid fire management. However, the relationship between low biomass and severe fires was less apparent when influenced by climate change. Overall, high severity fires were more common under altered climatic conditions even with reduced biomass across the landscape. Studies that investigate effects of climate change on barrens distribution and their ability to mediate wildfires may impact management practices in the region as climate change, fire management, and wildlife habitat continue to influence management decisions.

Keywords: jack pine barrens, climate change, LANDIS-II, fire management

Objectives

The objectives of this study were designed to address the JFSP GRIN project announcement No. FA-FON0014-0003 task statement topic "climate change and fire (e.g., fire behavior, fire effects, fire regime)."

The questions addressed by the study specifically investigated effects of climate change on the creation of jack pine barrens and their ability to mediate subsequent wildfires.

Question 1: How might climate change affect the distribution of jack pine barrens in northern Lower Michigan? Little is known about how jack pine barrens are formed on the landscape. We speculated that the extent of pine barrens on the landscape is spatially and temporally variable, and that the size and arrangement of pine barrens changes with time. Further, we hypothesized that severe or overlapping fire events lead to regeneration failure and the creation of barrens or open areas. We also hypothesized that temperature and precipitation changes associated with climate change will lead to more fires, and thus create more barrens, although there may be a point at which extensive fire frequency leaves the landscape altered beyond its natural fire regime.

Question 2: How are fire severity and spread affected by jack pine barrens and how might climate change alter this relationship? In northern Lower Michigan, fire-regenerated landscapes are characterized by dense stands of jack pine interspersed with large, open barrens similar in structure to man-made fuel breaks (Figure 1), but little research has been conducted to investigate the impact of fire-established barrens on fuel spread or severity. We addressed this knowledge gap by quantifying fire severity and extent with proximity to pine barrens on landscapes modeled using historical climate conditions and climate predicted by climate change scenarios. We hypothesized that the presence of barrens would act as a deterrent to future fires in the same stand. We expected the severity and extent of fires to decrease with proximity to barrens across all scenarios, and that climate change would not disrupt the ability of barrens to act as fuel breaks.

Figure 1. Characteristic jack pine barrens landscape in northern Lower Michigan.

Background

Jack pine barrens were historically common features of fire-adapted, jack pine-(*Pinus banksiana*) dominated ecosystems in the Highplains Subsection of northern Lower Michigan (Figure 2). Large glacial outwash plains with xeric, acid, sand soils of the Grayling series support jack pine-dominated ecosystems where the dominant tree species reproduces via fire-adapted, serotinous cones. The landscape structure in this region was historically maintained by frequent, stand replacing wildfires (Cleland et al. 2004, Simard & Blank 1982) and was characterized by open areas dominated by sedges, grasses, forbs, and low shrubs characteristic of savanna or prairie ecosystems within dense, jack pine forests (Whitney 1986, Houseman & Anderson 2002). Fire suppression in the 20th century sharply reduced the extent of early-successional stands, also primary breeding grounds for the Kirtland's warbler (*Setophaga kirtlandii*). The designation of

Kirtland's warblers as federally endangered in 1967 was followed by extensive management of jack pine plantations to provide habitat; today nearly 80,000 ha of land are managed for Kirtland's warbler habitat in the region. Large barrens have rarely been included in management plans and have been nearly eliminated across the region due to extensive establishment of plantations and decades of fire suppression. Open areas such as barrens can act as refugia for grassland species and potentially as fuel breaks for wildfires, facilitating wildfire management in a populated, fire-prone region while also maintaining landscape diversity. Many studies have investigated the importance of barrens on plant and animal communities (Probst & Weinrich 1993, Houseman & Anderson 2002), but few have focused on effects pine barrens may have on wildfire spread and manageability across the landscape.

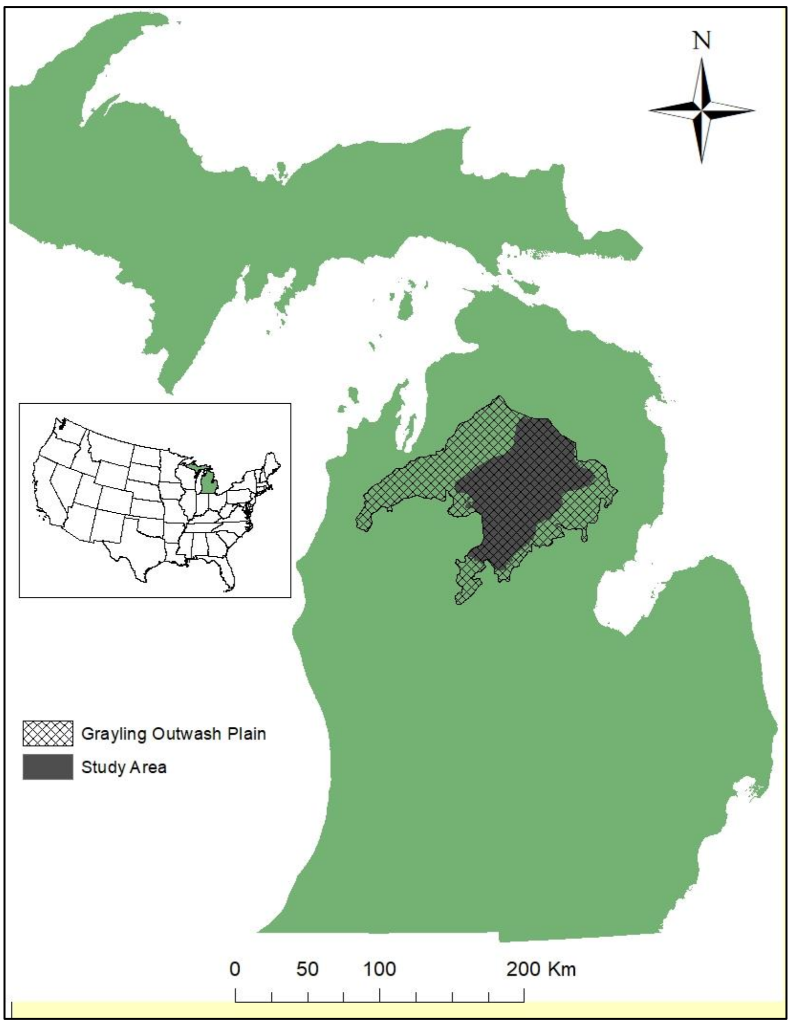

Figure 2. The study area in northern Lower Michigan and the extent of the Grayling Outwash Plain.

Effects of climate change are increasingly evident across temperate zones, and forest management agencies are being charged with stewardship of landscapes in a state of flux (Scheller and Mladenoff 2005; Iverson and McKenzie 2013). With many climate projections accompanied by predictions of larger, more frequent wildfires it is imperative to study effects of landscape structure on fire spread to aid in adaptive fire management. However, effects of climate change on barrens distribution are unclear (Figure 3). If fires increase in occurrence or severity in response to rising temperatures, the extent of barrens may increase. However, there is evidence that low-lying areas of the landscape produce frost pockets that discourage woody plant establishment; increased temperatures may reduce the negative effects of these frost pockets, enable establishment, and reduce barrens occurrence. Further, increased precipitation may reduce exclusionary effects of the excessively-drained sands that characterize the regions' soils and facilitate woody plant establishment, and thus reduce overall barrens distribution. Clearly, it is difficult to predict effects of climate change on barrens distributions.

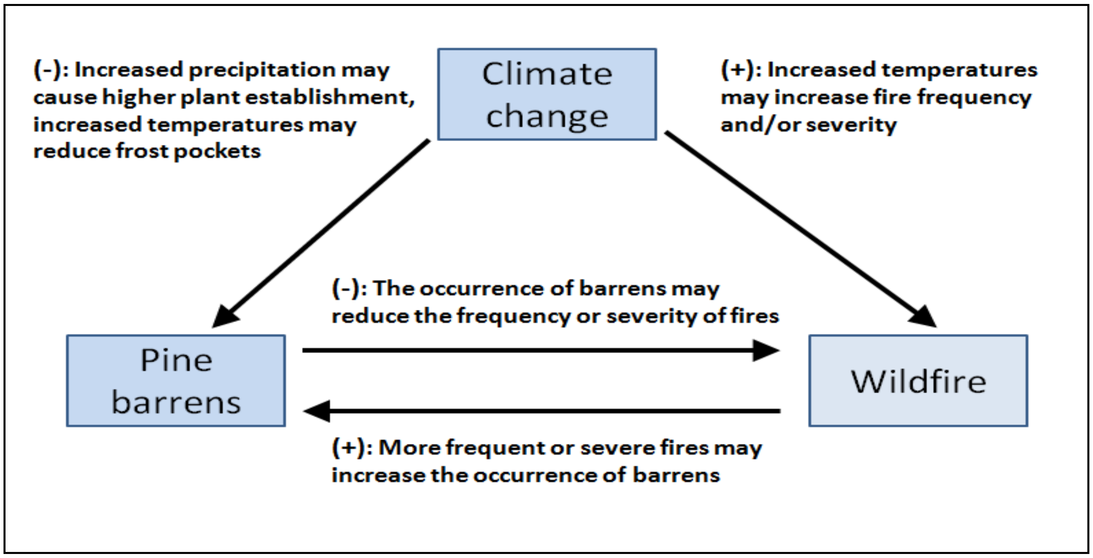

Figure 3. Conceptual diagram of the relationship between climate change, wildfires, and jack pine barrens.

Historically, jack pine barrens may have functioned as natural fuel breaks on a landscape prone to frequent, stand-replacing wildfires. By modeling fires on the presettlement landscape, the full potential of pine barrens' ability to mediate wildfire spread may be examined without the confounding variables of modern land use and fire suppression. Comparisons to landscapes modeled after climate change projections can predict changes in forest structure and can be useful for fire management in a region that, although highly managed, still has frequent, high severity fires. Land managers in the region have shown increased interest in barrens restoration efforts, and federal and regional management strategies have cited the restoration of historical range of structural variability in fire-adapted ecosystems as a priority (NCWFS 2013; MDNR 2015). Particularly in light of climate change predictions, inclusion of barrens in management areas could help fire managers and firefighters control wildfires while also fulfilling their mandate to restore natural landscape variability.

Materials and Methods

This project examines the distribution of pine barrens on landscapes modeled using presettlement ecosystem distributions, and both historical and projected climate conditions to investigate the relationship between jack pine barrens, wildfires, and climate change. We used data taken directly from General Land Office (GLO) Public Land Surveys and delineated into ecosystem type and stand age to determine historical distributions of forest communities (Austin et al. 1999; Maclean and Cleland 2003; Tucker et al. 2016). Frequently used to characterize presettlement forests (Schulte & Mladenoff 2001; Bolliger et al. 2004), GLO survey notes act as a snapshot of the forest landscape prior to significant settlement, logging, and land cover conversion and have the potential to serve as an ecological baseline for restoration efforts and management decisions. To determine effects of climate change, we used two general circulation models to determine future climate: the Hadley Centre model (HadCM3; Gordon et al. 2000) and the Canadian Climate Centre model (CGCM3; Flato et al. 2005). The HadCM3 model predicts greater precipitation and warming than the CGCM3 model (Mearns et al. 2007). In both models the A1FI scenario represents a fossil-fuel-intensive scenario for future climate, and overall predicts increased temperature in a range from 2.4°C to 6.4°C over current averages (IPCC 2007). We used this more extreme scenario to allow assessment of the largest potential differences between historical and future climate.

The propagation of fire-created pine barrens on historical and climate change affected landscapes was projected and quantified using LANDIS-II to model wildfire disturbance effects on the landscapes. Spatially explicit, stochastic simulations of forest cover and disturbance processes via modeling programs such as LANDIS-II allow for quantification of landscape metrics and disturbances at large spatial scales, and can be useful for predicting landscape changes due to climate change (Sturtevant et al. 2009). The Biomass Succession (Scheller and Mladenoff 2004) and Dynamic Fuels and Fire System (Sturtevant et al. 2009) extensions in LANDIS-II were used to simulate landscape disturbance patterns for the study area. The Biomass Succession extension produces output logs of landscape metrics including aboveground biomass and raster maps at each user-defined time step that detail annual net primary productivity (ANPP). The spatial distribution of regions with low ANPP were determined to represent barrens. The Dynamic Fire System extension generates logs of fire events and severity and fire severity maps for each fire time step, and allowed for quantification of the spatial relationship between fire severity and barrens establishment.

To address the first question (How might climate change affect the distribution of jack pine barrens in northern Lower Michigan?), we simulated the historically-based landscape for 300 years using 30-year normals for temperature and precipitation (PRISM 2012) to establish a baseline landscape. We then simulated the same landscape using temperature and precipitation predicted by the HadCM3 model. To assess the spatial and temporal variability of barrens establishment we compared the amount of area associated with low ANPP at several time steps using the area calculator in ArcMap (10.4; Esri 2016). We compared the landscapes visually to determine the extent that climate change affected spatial barrens distribution. We also compared mean aboveground biomass for both landscapes for all time steps visually and using a Welch's t-test (Welch 1951).

To address the second question (How are fire severity and spread affected by jack pine barrens and how might climate change alter this relationship?), we used the same 300-year simulations to investigate fire severity. We compared output raster maps visually to investigate effects of areas with low ANPP on future fires in the same region of the landscape. We also used a Welch's t-test (Welch 1951) to compare the fire severity of all fires for all time steps for the two landscapes.

Results and Discussion

Effects of climate change on barrens distribution did not entirely support our hypotheses. We hypothesized that the distribution of barrens would be variable both spatially and temporally, and as expected we found that barrens are not spatially static on the landscape. At each time step the areas of lower ANPP were not consistently aligned, suggesting that fires in previous time steps do indeed predict future areas of low productivity and that barrens distribution is variable through time, although the overall area of barrens coverage on the landscape remained surprisingly consistent even when the arrangement of barrens changed. We expected the climate change-affected landscape to produce more fires, but that was not the case (Figure 4). However, the HadCM3 simulated landscape had a significant increase in the severity of fires ($t_{(26038)} = -5.633$, $p < 0.0001$; Table 1) as described by the fire severity index, which is based on the amount of crown fraction burned and rate of spread of fires (Sturtevant et al. 2009). There were 20 fires more severe than any of the fires that had burned under historical climatic conditions. Increased fire severity can lead to reduction of the structural variability historically found post-fire in the region, where scattered, unburned patches frequently persist within a heterogeneous matrix of burn severities (Spaulding and Rothstein 2009; Kashian et al. 2012; Kashian et al. 2017).

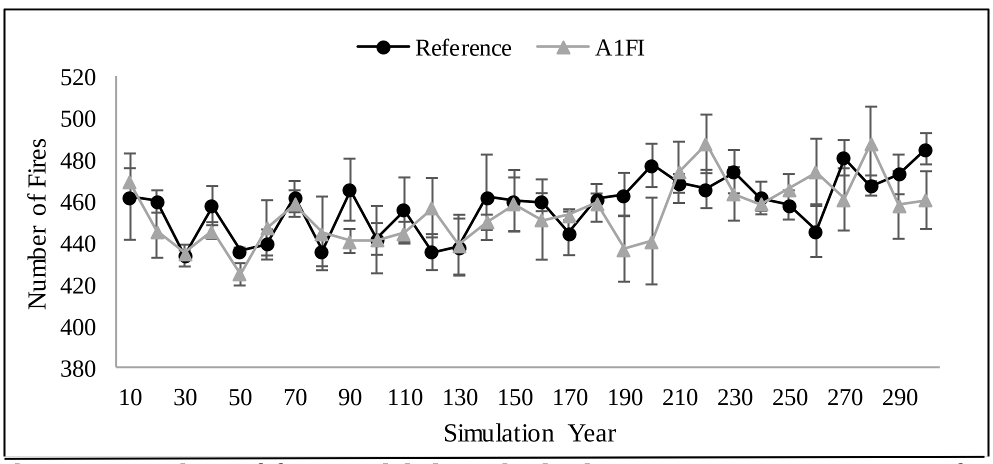

Figure 4. The mean number of fires modeled on the landscape at 10-year time steps for 300 years of simulations. Error bars represent standard error. "Reference" denotes conditions simulated using historical climatic data, "A1FI" denotes conditions simulated using climatic conditions predicted by the HadCM3 A1FI scenario.

Table 1a. Metrics of fire severity from the landscape derived from historical climatic conditions (PRISM 30-year normal data covering 1981-2010) for the full 300-year simulation. Total number of fires = 13,733.

Occurrences (n)	Maximum Severity	Minimum Severity	Mean Severity	Mean Number of Cohorts Killed	Mean Number of Sites
14	3.7	3.0	3.2 (0.06)	86.7 (15.6)	137.7 (19.6)
72	2.9	2.5	2.6 (0.02)	140.1 (10.2)	167.3 (5.1)
241	2.4	2.0	2.2 (0.01)	154.6 (7.1)	175.3 (2.1)
659	1.9	1.5	1.7 (0.01)	128.4 (3.6)	182.4 (1.4)
4321	1.4	1.0	1.1 (0.001)	68.3 (1.3)	193.9 (0.5)
8426	0.9	0.5	0.99 (0.0003)	34.2 (0.7)	192.4 (0.4)

Table 1b. Metrics of fire severity from the landscape modeled using HadCM3 A1FI scenario climatic conditions for the full 300-year simulation. Total number of fires = 13,612.

Occurrences (n)	Maximum Severity	Minimum Severity	Mean Severity	Mean Number of Cohorts Killed	Mean Number of Sites
20	4.95	4.0	4.5 (0.07)	48.9 (7.2)	166.5 (10.3)
15	3.9	3.5	3.8 (0.04)	72 (10.7)	167.8 (11.6)
31	3.4	3.0	3.2 (0.03)	68.5 (8.6)	176.9 (7.7)
96	2.9	2.5	2.7 (0.01)	113.6 (13.5)	172.5 (5.2)
258	2.4	2.0	2.2 (0.01)	134.5 (6.4)	178.4 (2.2)
699	1.9	1.5	1.7 (0.01)	113.6 (3.3)	184.6 (1.3)
4706	1.4	1.0	1.1 (0.002)	63.3 (1.2)	194.2 (0.5)
7787	0.9	0.5	0.9 (0.0003)	18.9 (0.6)	191.2 (0.4)

While increased fire severity did not result in overall higher coverage of barrens, there was a significant reduction in mean aboveground biomass across the entire climate change-affected landscape ($t_{(195.97)} = -14.881$; $p < 0.0001$; Figure 5). The differences in biomass between the landscapes suggest that either establishment and persistence may become more difficult given the climatic conditions predicted by the HadCM3 model, or that the cumulative effect of increased fire severity over multiple time steps may result in reduced biomass and ANPP overall. This result is contrary to carbon fertilization hypotheses that predict increasing NPP resulting from higher atmospheric carbon associated with global climate change (Bonan 2008). In northern Lower Michigan, there appears to be a reduced capacity of forests to uptake carbon, likely due to the already dry nature of soils and effects of increased evaporation related to rising temperatures. In this way forests in this region are likely to experience carbon storage effects more similar to tropical forests, where evaporative drying reduces NPP, than to boreal forests, where rising temperatures cause increased NPP (Fung et al. 2005).

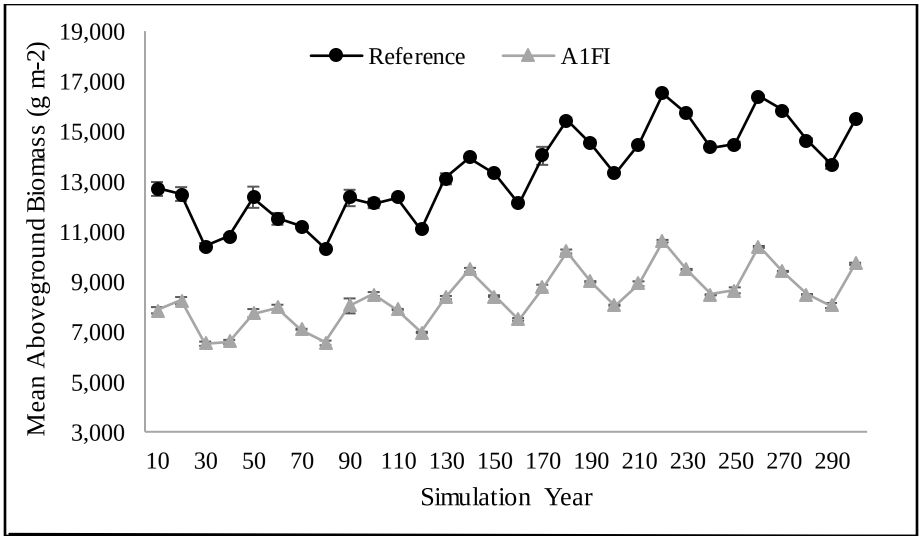

Figure 5. Mean aboveground biomass modeled on the landscape at 10-year time steps for 300 years of simulations. Error bars represent standard error. “Reference” denotes conditions simulated using historical climatic data, “A1FI” denotes conditions simulated using climatic conditions predicted by the HadCM3 A1FI scenario.

Although the area of severe fires over any given time step (10 years) was not large in magnitude, the cumulative effect of decades and centuries of overlapping or adjacent fires likely produced the extent of historical barrens (Figure 6). Effects of pine barrens on the occurrence of future fires were consistent with our hypotheses. Both scenarios showed that areas with low ANPP reduced the occurrence of fires in the same region for multiple decades (Figures 7 and 8). These results suggest that retention of natural, fire-created barrens and/or emulation of the structure of barrens through harvesting may aid in fire management efforts.

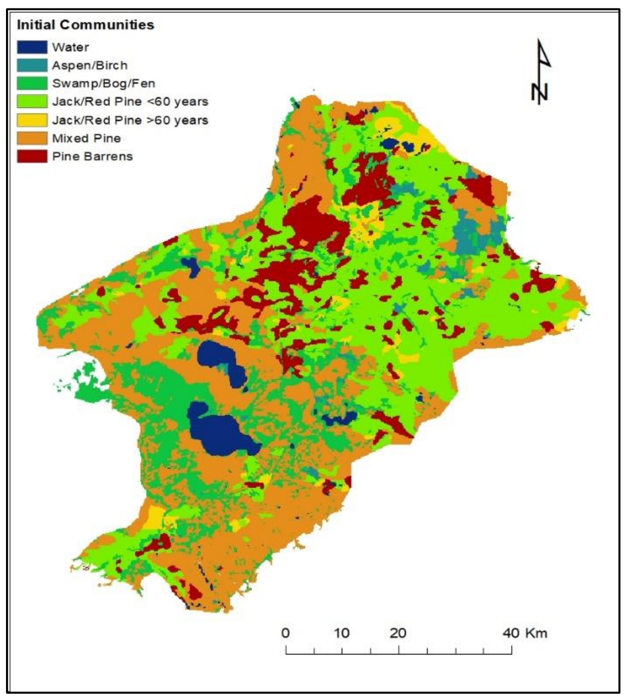

Figure 6. Historical distribution of ecosystems based on GLO survey notes.

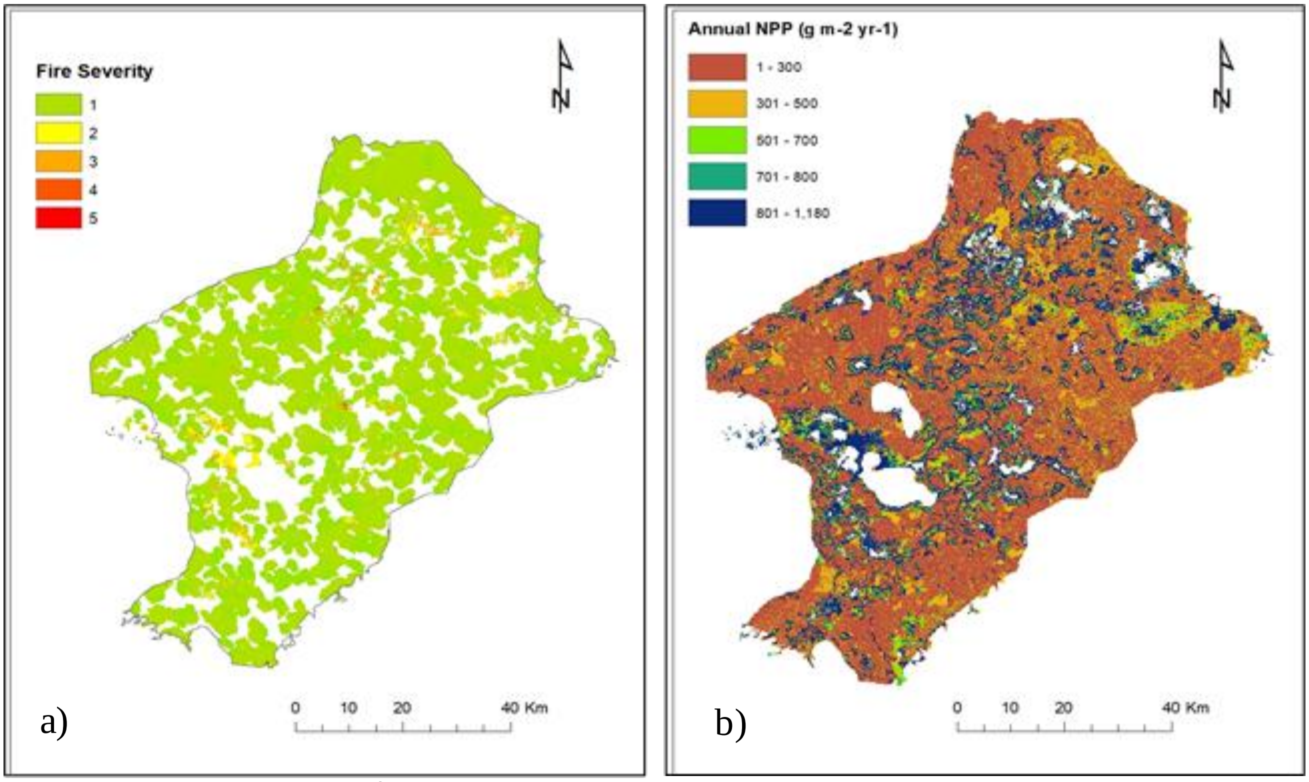

Figure 7. a) Fire severity index for two time steps combined (years 270 and 280) and b) annual net primary productivity (NPP) in the preceding time step (year 260) for the landscape simulated using historical, 30-year normal climate conditions. Index values are based on the crown fraction burned (CFB) and rate of spread (ROS) of fires: 1 is least severe and 5 is most severe.

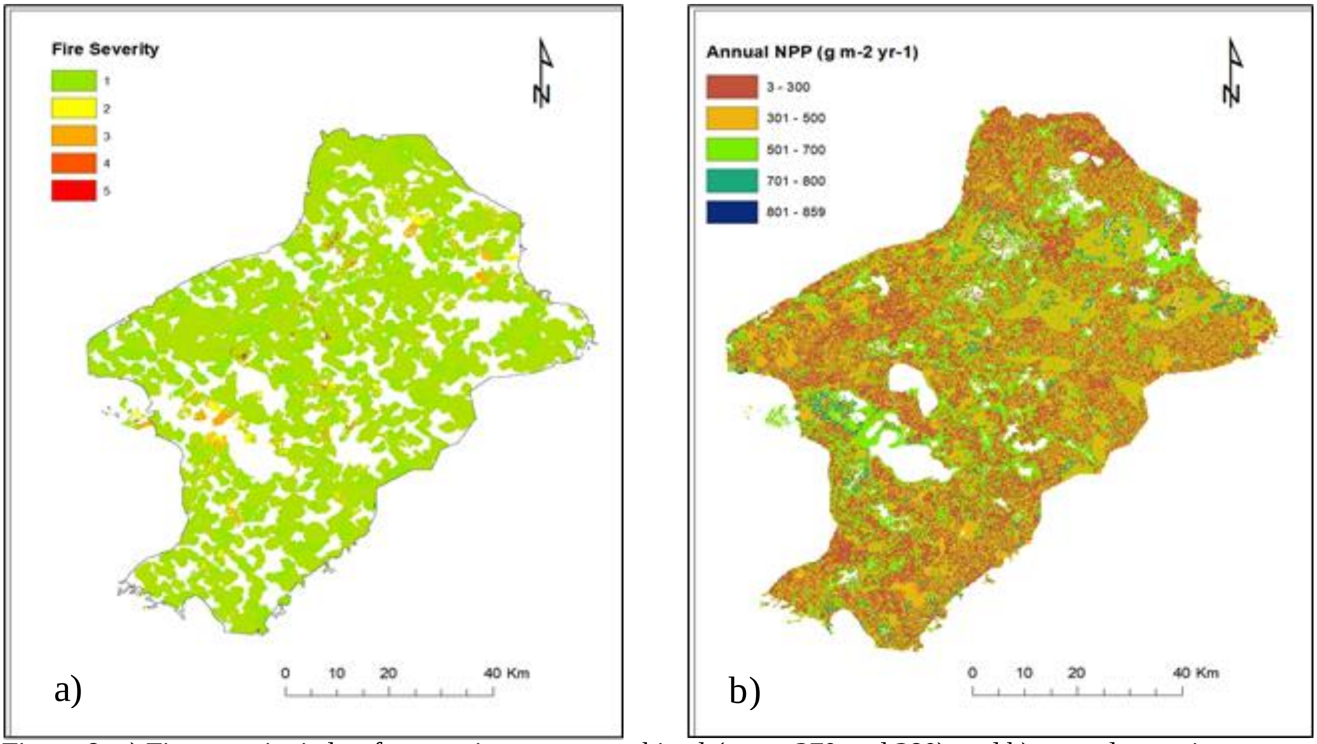

Figure 8. a) Fire severity index for two time steps combined (years 270 and 280) and b) annual net primary productivity (NPP) in the preceding time step (year 260) for the HadCM3 A1FI scenario projected landscape. Index values are based on the crown fraction burned (CFB) and rate of spread (ROS) of fires: 1 is least severe and 5 is most severe.

Science Delivery

Over the course of the project we have worked to communicate the process and findings of the study in several venues. Initially the student investigator traveled to the USFS Northern Research Station in Rhinelander, WI to discuss the project with LANDIS-II experts at the Institute for Applied Ecosystem Studies. She also provided an overview of the project and preliminary results in an oral presentation to management practitioners and academics at a meeting at the Seney National Wildlife Refuge, Seney, MI. The student investigator gave an oral presentation at the International Association for Landscape Ecology annual symposium in Baltimore, MD. The forthcoming refereed publication (in preparation) will be shared with the Lake States Fire Science Consortium for inclusion in their publication database, and the student investigator will present a webinar in their annual series to present the results. Finally, the student investigator plans to attend the Kirtland's Warbler Conservation Team Meeting in Grayling, MI (September, 19-20, 2017) to discuss the project with land managers and other partners in the region.

Conclusions

Key findings

The objectives of the study, to investigate the role of barrens on fire and the effect of climate change on the relationship, were met. The arrangement of barrens on the landscape fluctuated throughout the duration of the simulations runs, and displayed the ability of fire to cumulatively affect the amount of aboveground biomass for decades. Patterns of vegetation and structure are in this way inextricably tied to the fire regime in the region. Climate change may therefore have significant, long-lasting effects evident even at broad scales. Increases in fire severity resulting from altered climate conditions may be particularly dangerous in areas where fire-prone ecosystems abut cities, towns, and other occupied areas. Using results from this project, managers may be able to mitigate some of the danger to the surrounding populace while also incorporating historically-relevant structural heterogeneity.

Implications for management

The historical extent of barrens is derived from GLO survey notes, and therefore represents a moment in time rather than the full range of historical variability; coverage of barrens likely fluctuated over time as a result of climatic conditions. The current landscape, after decades of fire suppression and Kirtland's warbler habitat plantation management, features an extent of barrens well below what would have been expected on the historical landscape (Houseman and Anderson 2002). Given increased interest in adaptive management practices that incorporate ecosystem processes and diversity (Bocetti et al. 2012), prioritization of open barrens within the typically-dense structure of Kirtland's warbler habitat plantations could restore landscape structural diversity while providing a tool for fire management within the context of a changing climate.

Future research

Several additional aspects of the work will be included in the refereed publication. Effects of frost pockets, or low-lying areas of the landscape, are likely to heavily impact the persistence of barrens over long time periods and should be modeled within LANDIS-II. Frost pockets are produced not by the magnitude of the elevation, but by the change in elevation relative to the surrounding landform, where shallow depressions collect cold air that impedes plant establishment and growth. This topographical feature is difficult to model in LANDIS-II and will require additional time spent on simulations. Also, the CGCM3 climate model and landscape metrics that more clearly quantify differences between landscapes are still under investigation, and will be included in the refereed publication. More broadly, there is a need to investigate effects of climate change on regeneration and growth of jack pine as a species, and future work should explore the mechanisms behind the significant reduction in NPP and aboveground biomass predicted by this study. Large-scale loss of biomass could significantly affect the region economically as well as ecologically, as tourism and logging both fuel much of the regions' economy.

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Appendix B: List of Completed/Planned Scientific/Technical Publications/Science Delivery Products

Deliverable Type	Description	Status
Spatial dataset	Maps of pine barrens and fire severity modeled from historic and climate change-projected landscapes in northern Lower Michigan	In progress, completion expected late 2017
Refereed publication	Can the arrangement of jack pine barrens mediate the spread of wildfires under various climate scenarios? (Tucker and Kashian) - will be submitted to Lake States Fire Science Consortium for archival and dissemination	In preparation, to be submitted early 2018
Conference presentation	Madelyn Tucker oral presentation at International Association for Landscape Ecology Annual Meeting in Baltimore, MD - awarded NASA-MSU Professional Enhancement Award to attend/present	Complete
Management agency communication/presentations	• Presentation to managers and academics at Seney National Wildlife Refuge, Seney, MI. • Kirtland's Warbler Conservation Team meeting (scheduled Sept. 19-20, 2017) • Lake States Fires Science Consortium webinar (planned for 2018)	Complete and ongoing
Ph.D. thesis	Effects of disturbance on jack pine-dominated ecosystems of northern Lower Michigan, USA: wildfire, climate change, forest management	In preparation, anticipated Spring 2018
JFSP final report	Can the arrangement of pine barrens mediate the spread of wildfires under various climate change scenarios? JFSP Project ID: 14-3-01-32	Complete

Appendix C: Metadata

Data used for this project includes many landscape parameters such as community composition, landforms, fire weather data, and topographic features. These data were gathered from several sources and are stored in both raster and .csv formats. The data will be submitted to the US Forest Service Research Data Archive for storage. Metadata in the Federal Geographic Data Committee (FGDC) format will be submitted with this report and to the US Forest Service Research Data Archive.